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Oscillation Flow Induced by Underwater Supersonic Gas Jets from a Rectangular Laval Nozzle

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Abstract

In present work, direct measurements of the interfacial behavior of water-submerged gas jets, with nozzle operated in over-expansion to highly under-expansion conditions, were performed using high-speed digital photography. The experimental results show that the two low-frequency oscillations, which are so called jet necking/bulging and necking/back-attack phenomenon, are also found in the region near present rectangular nozzle exit. As the nozzle pressure ratio increased, two distinct flow regimes can be observed: One that showed unstable gas/water interfacial characteristics for nozzle pressure ratio, NPR or $P_o/P_a \leq 10.17$ when the jet pattern showed similar shape as the one issuing from axisymmetric nozzles, and the other with stable jet pattern for NPR > 18.48 when a 3D cross-like cross section jet gas/water boundary started to form and grow from the nozzle exit. Finally, numerical analysis on shock wave structures of the experimental nozzle models was carried out, and the submerged jet gas/water interface characteristics show good agreement with the jet boundaries predicted by numerical simulations. The numerical results indicate that the over-expanded flow in the four corner regions as well as the recompression shock wave may play a dominant role in the interface instability to result in necking/bulging and necking/back-attack phenomenon during over-expanded to slightly under-expanded conditions.

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Keywords: Submerged supersonic gas jet; Rectangular Laval nozzle; Jet oscillation; High-speed digital photography

1. Introduction

Investigation on the jet structure and hydrodynamic stability of submerged gaseous jets and their effects concerns

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Nomenclature

RANS	Reynolds-averaged Navier-Stokes
NPR	Nozzle pressure ratio
P_o/P_a	Nozzle pressure ratio via ambient pressure
P_e/P_h	Exit pressure ratio via local back pressure underwater
C-D	Convergent-Divergent
W	Width of the C-D nozzle, mm
h	Exit height of the C-D nozzle, mm
L	Length of the Spike, mm
l	Length of the cowl, mm
γ	Gas specific heat ratio
Ma	Mach number
A_e	Nozzle exit area, m2
A_t	Nozzle throat area, m2
A_e/A_t	Nozzle area ratio
P_b	Local ambient pressure, Pa
P_{ON}	Nozzle stagnation chamber pressure, Pa
P_{oj}	Jet stagnation pressure, Pa

quite a variety of engineering applications, such as metallurgical processes [1], [2], underwater propulsion [3] and so on [4]. The metallurgical industry uses submerged gas jet for liquid metal stirring and gas-metal reactions as the high speed gas jet enhances mixing efficiency through the high surface to volume ratio of the bubbly mixture [5], [6]. Since the focus of submerged gas injection in most cases is usually on enhancing mixing and mass transfer, rectangular jets are excellent for achieving these goals. Zaman et al. [7] has reported single phase rectangular jets naturally exhibit higher mixing at the interface than circular jets when the aspect ratio increases past approximately 10. Although most studies have focused on axisymmetric [8], [9] or planar [10] gas jets injected into still liquid, the present study focuses on the injection of a rectangular supersonic gas jet exhausted into still water. In particular, we seek to characterize the effects of shock structure behind the nozzle exit flow region on the interfacial stability, especially on the severe jet expansion/"back-attack" phenomena.

The fluid mechanics study of unsteady phenomena and mechanisms in the submerged gas exhaust systems actually began in the area of metallurgy when tuyere refractory erosion was found [11], [12]. Concerning the problem of refractory erosion, several water-model experiments were conducted. Hoefele et al. [13] carried out the first experimental research on characterizing the flow regime of underwater gas jets from a submerged tuyere by high speed photography and pressure measurements. Both straight and convergent-divergent tuyeres were used. They found that the tuyere erosion could be reduced by pushing the gas jet away from the wall surface through increasing the jet velocity. Ozawa et al. [14] and Mori [15] continued the experiments, and found that the jet experiences bubbling-to-jetting transition when the jet velocity becomes sonic. Aoki et al. [16] first identified the "back-attack" phenomenon of an underwater sonic gas jet, that is, the jet periodically blows back to impact on the tuyere surface, and described it as the major factor of causing tuyere refractory erosion. Based on the work of Aoki et al. [16], Yang et al. [13, 14] studied the "back-attack" phenomena and associated tuyere refractory erosion; they found that the erosion is caused by cavitation during smaller bubbles collapse on the surface.

In recent years, Dai et al. [15] and Shi et al. [20]-[25] expanded the experimental researches of the past studies [13]-[18]. While only convergent conical or straight type of nozzles were used in the previous water-model experiments, Shi et al. [20]-[25] performed experimental studies on the submerged gas jet issuing from both supersonic and sonic nozzles. According to their work, it has been found that the "back-attack" always appears in underwater supersonic gas jet, and no matter how the gas jet is in under-expansion, full-expansion or over-expansion [19], [22]. There are many explanations for the underling physics of the "back-attack" phenomenon. Shi et al. [24], [25] have suggested that the "back-attack" can be a shockwave or jet expansion feedback phenomenon, while Tang et al. [26] have described the "back-attack" is a backward flow generated due to the injected gas has difficulties approaching the downstream region after the necking/breaking process. These debatable explanations indicated the necessity to study the problem from the point of view of aerodynamics and fluid mechanics.

While the effects of Mach number [19], [20], aspect ratio [20], and nozzle pressure ratio [19], [23]-[24], [28] on the interfacial stability or the "back-attack" phenomena have been studied extensively for quite some time, the effect of shock structures at the nozzle exit flow regime formed by supersonic gas jet has received very little attention. However, the measurements of static pressures in a submerged under-expanded gas jet by Loth and Faeth [8] and Qi at al. [27] provide strong evidence that a shock wave cell structure for external expansion is present in the jet. Furthermore, experimental study of Dai et al. [19] indicated that supersonic gas jets in still water induce large pressure pulsations upstream of the nozzle exit and the presence of shock-cell structure in the over- and under-expanded jets leads to an increase in the intensity of the jet-induced hydrodynamic pressure. Following the idea of Dai et al. [19], Shi et al. [24] have indicated that the process of supersonic air jets into water causes large flow oscillation, which can be related to shock waves feedback in the gas phase. These experimental findings have indicated that the complicated shockwave structures may play an important role in the distortion of submerged supersonic gaseous jets and associated strong pressure pulse behind the nozzle exit.

For a supersonic gas jet issuing from rectangular nozzle, while jets submerged in liquid are not understood very well, single phase flow systems are extensively analyzed [29]-[32], primarily in connection with noise suppression or thrust vector control for jet engines. Such jets have also been studied with respect to passive mixing [33]. Teshima studied the structure of under-expanded jets from sonic orifices [34], [35], and found that the jets expand most prominently in the major and minor axial directions, resulting in a cross-shaped cross section. Seiji Tsutsumi et al. [36] numerically and experimentally studied the structure of under-expanded jets from square nozzles; it was shown that the first shock cell is composed of two types of shock waves, intercepting shock waves and recompression shock waves. The jet expands almost two-dimensionally on the symmetry planes, whereas shock waves suppress expansion on the diagonal planes, resulting in a cross shaped jet cross section. This cross-like jet shape differs considerably from the shape of jets issuing from axisymmetric nozzles; Figure 1 shows the shock surface. The injection of gas into water will introduce additional level of complexity in the jet flow regime, which is marked by oscillation of the gas/water interface. Thus, oscillation flow induced by underwater supersonic gas jets issuing from rectangular nozzles and axisymmetric nozzles are likely to be different.

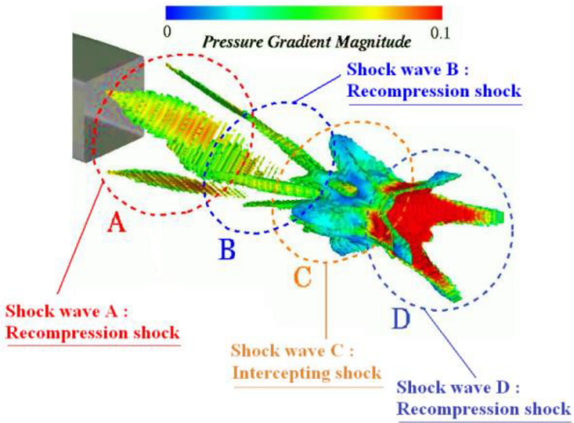


Fig. 1. shock surface in the region downstream of an under-expanded Mach 2.2 square nozzle [35].

The goal of the present paper is to study the flow structures, in particularly, the unsteady interfacial characteristics of the submerged rectangular supersonic gas jet. Unlike the work carried out by Weiland [20], we focus on the low-frequency, large-amplitude oscillation characteristics, which are the so called jet necking/bulging or necking/"back-attack" phenomena. Compressibility effect, by the variation of nozzle pressure ratio, is varied to account its effect on the gas/water interface oscillation, which is measured by high-speed photography, and no measurements of the internal jet structure were taken. An additional numerical analysis on shock wave structures of the experimental nozzle models is carried out to make a better understanding of the relevant phenomena and mechanics.

2. Experimental setup and numerical methods

2.1. Nozzle geometry

The nozzle studied in present paper was a subscale, non-axisymmetric, two-dimensional C-D nozzle with a throat height h_t of 3.0 mm, an area ratio, A_e/A_t, = 1.82, and a constant width of 6.0mm. Based on one-dimensional theory, the nozzle gives a design nozzle pressure ratio, NPR, of 8.999 and an exit Mach number of 2.09 under a specific heat ratio of 1.4. Detailed configurations of the nozzle model are shown in Fig. 2, and the origin of (x, y) coordinates is located at the inlet of the nozzle.

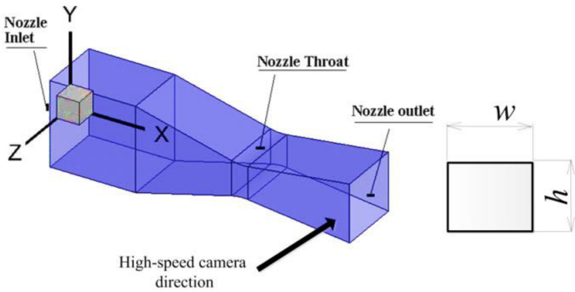


Fig. 2. Schematic of the experimental nozzle geometry.

2.2. Experimental methods and facilities

The experiments were conducted in a general experimental platform for underwater gaseous jet study. The present experimental setup is shown in Fig. 3 and consists of High pressure Nitrogen bottles and a Pressure reservior, pressure-adjusting valves, a fast acting valve which impulsively switched on the gas injection, manual valves for security, an open water tank, a nozzle assemblage supported in the water tank, pressure and temperature transducers, and a high speed camera (Mega Speed type, operated at a framing rate of 1/1000s or 1/2000s during 8s for one run) which recorded shadowgraph images of the underwater jet. The water tank is made of stainless steel plates and has a size of 3500mm, 1500mm, and 1600mm in the length, width and height direction, respectively. An optical-quality glass window has a size of 500mm multiply 500mm was designed in the tank sidewall by the camera side for the submerged gaseous flow visualization and flow diagnostic measurements. Water with a constant level of 1100mm in the tank was at atmospheric pressure and local room temperature. The C-D nozzle was horizontally held at a constant submerged depth of 700mm, gives a local back pressure of 1.0817×10^5Pa. Implement similar as wave breaker used in Ref. [20] was not included in present experiments, Past researchers [10], [19]-[20] has shown that the wave dampers or breakers do little to change the flow characteristics.

Table 1. Flow conditions, all jets were shot at 700mm underwater depth and the properties shown here were calculated for the exit of nozzle.

_	P_c, Mpa	NPR	P_e, $\times10^5$Pa	P_e/P_h	T_a, k	Ma	Velocity, m/s	Re, $\times10^5$	Operating condition
Rec.	0.80	7.39	0.89	0.82	300.1	1.96	512.26	3.64	Over-expansion
	0.97	8.97	1.08	1	300.2	2.09	530.13	3.99	Full-expansion
	1.10	10.17	1.22	1.13	300.2	2.17	540.45	4.21	Under-expansion
	2.10	19.41	2.33	2.16	300.2	2.58	586.94	5.50	Under-expansion
	3.02	27.92	3.36	3.10	300.1	2.82	608.25	6.32	Under-expansion

The tests were controlled by a LabVIEW program which simultaneously triggered the high speed camera, monitored nozzle total pressure, and opened the fast acting valve which delivered gaseous nitrogen to the chamber.

This allowed for the establishment of an accurate reference time, and synchronization between the total pressure transducer and the recorded images. By changing the chamber pressure, P_c, just upstreamed the nozzle assembly, jets with different velocities can be obtained. The test matrix is shown in Table 1 where all the flow properties, such as the Mach number, *Ma*, static pressure, P_e, and the Reynolds number, *Re*, et al. are calculated based on the nozzle exit properties. Here the Mach number and Velocity use the flow properties of post-wave at the exit of nozzle, if as a first approximation it was assumed that the pressure behind the incident shock or expansion wave becomes environmental, and the equivalent Hydraulic diameter based on the exit of nozzle is used to the characteristic length scale for Reynolds number calculation.

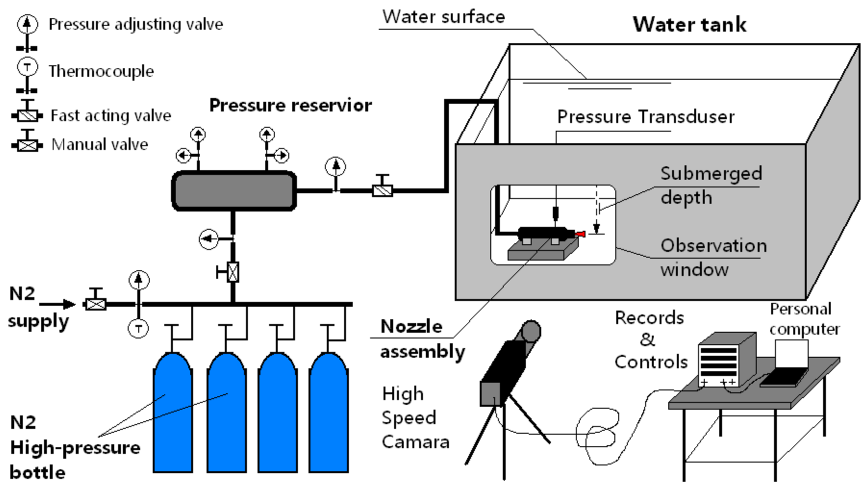


Fig. 3. The experimental setup of underwater gaseous jets.

2.3. Numerical procedure

3D unsteady numerical simulations have been carried out using the ANSYS FLUENT 13.0 finite volume computational fluid dynamics code. It solves the Reynolds-averaged Navier-Stokes, RANS, equations with different turbulence models and numerical schemes. In our present numerical study, the convective terms were discretized using a upwind scheme for all equations, inviscid fluxes were derived using the Roe flux splitting, achieving the necessary upwinding and dissipation close to the shock wave, whereas the viscous fluxes were evaluated using a central-difference scheme. Both schemes were second-order spatially accurate. A second-order implicit scheme was used for iterating the unsteady equations to the steady-state solution. The wall boundary layer was assumed to be turbulent, and the one-equation Spalart-Allmaras turbulence model was used here.

In order to perform 3D simulations of such a rectangular nozzle flow field, finite volume grids have been constructed using an algebraic grid generator software GAMBIT 2.4.6. Multi-block structured grids have been using in this calculation and are presented in Fig. 4. The computational domain included the convergent-divergent part of the C-D nozzle and the zone downstream. The fine H-grid is located in the area where the target jet structure appears, and total number of the grid was about 3.4 million at most.

The computational flow conditions matched the experimental conditions, the initial and boundary conditions are presented as follows: at the nozzle inlet boundary, stagnation pressure and temperature were imposed as physical boundary conditions. The exit boundary was constrained with pressure outlet boundary condition. Both the above parameters used the experimental data. The walls were specified to be non-slip and adiabatic solid boundary. The present work focuses on the influence of the nozzle pressure ratio on the steady-state shock structures as well as helping to understand their correlations with the jet boundary and the submerged jet instability; however, the transient data for each nozzle pressure ratio were excluded, although the computation was conducted with the unsteady RANS solver.

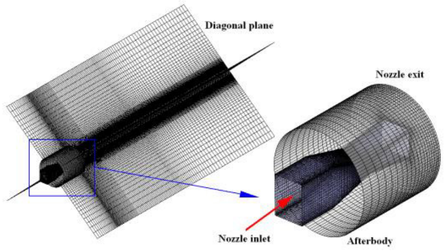


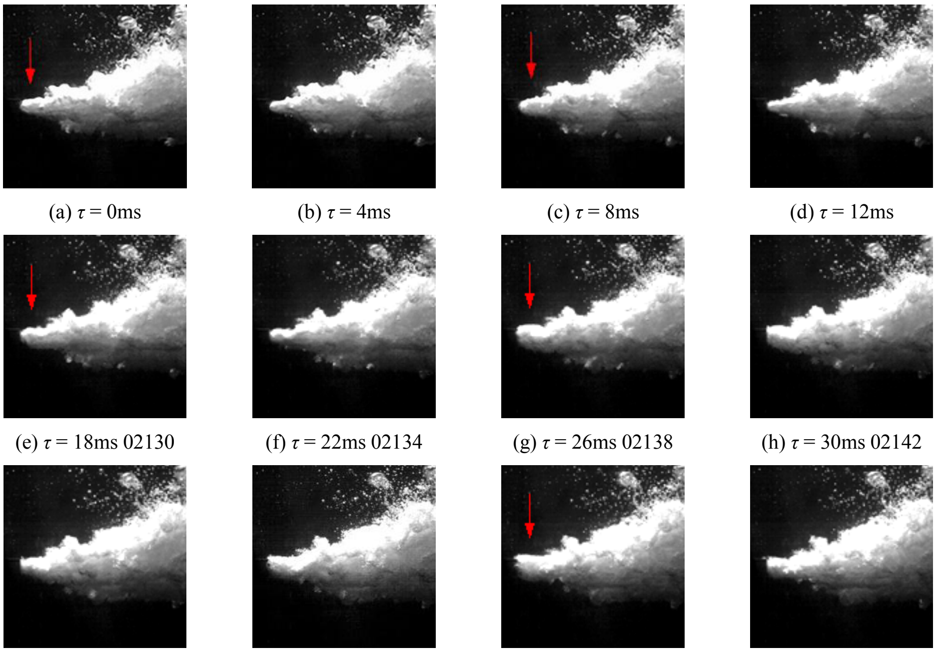
Fig. 4. Computational domain and mesh systems for the 3D simulations.

3. Results and discussion

3.1. Gas/water interfacial characteristics and instability

As the nozzle pressure ratio increased, we observed two distinct flow regimes: One that showed unstable gas/water interfacial characteristics for nozzle pressure ratio, NPR or $P_o/P_a \leq 10.17$ when the jet pattern showed similar shape as the one issuing from axisymmetric nozzles, and the other with more stable jet pattern for NPR > 18.48 when a 3D cross-like jet gas/water boundary started to form and grow from the nozzle exit.

Fig. 5 and Fig. 6 are the sequences of slightly under-expansion jets for 1.1Mpa case with a nozzle pressure ratio of 10.17, and the jet Necking/Bulging and Necking/Expansion-feedback phenomena are observed and presented, respectively. The experiments of lower nozzle pressure ratios give similar results and are excluded in this paper. For these NPR conditions, the jet vibration, reverse impact were much significant and played a dominant role in the rear flowfield of the nozzle.



(a) τ = 0ms (b) τ = 4ms (c) τ = 8ms (d) τ = 12ms

(e) τ = 18ms 02130 (f) τ = 22ms 02134 (g) τ = 26ms 02138 (h) τ = 30ms 02142

(i) τ = 32ms 02144 (j) τ = 36ms 02148 (k) τ = 40ms 02152 (l) τ = 44ms 02156

Fig. 5. High-speed photography of the jet Necking/Bulging phenomenon of a rectangular submerged under-expanded supersonic gaseous jet. Interframe time = 4ms. P_c = 1.1Mpa. The jet Mach number of post-expansion-wave at the nozzle exit is Ma = 2.17.

As shown in Fig. 5(b), (d), and (f), et al. when the jet is in a normal condition, the jet has a turbulent gas/water interface surrounding the core. The jet pattern generally follows the similarity law, i.e., and the gas/water interface grows almost linearly. This means that a supersonic gas jet from present rectangular Laval nozzle gives similar interfacial characteristics as the one issuing from axisymmetric nozzles in water for these NPR conditions. The jet Necking/Bulging phenomenon occurs as marked as the red arrows in Fig. 5(a), (c), and (e), et al. This bulged bubble will appear several times and not collapse while be swept downstream by the jet, which is also observed in both past experimental and numerical results [3], [8], [23]-[25] for submerged axisymmetric nozzles. The other flow characteristic is that once the jet Necking/Bulging phenomenon occurs, the diameter of the bulged bubble as well as the time interval between two bulge events increase. Shi et al. 0 attributed this non-linear oscillation to the shock waves system in the bulged bubble, where it is re-structured and the waves' energy is accumulated in a new way. However, He et al. 0 observed an opposite tendency during the continuous jet Necking/Bulging phenomenon sequences. It is indicated that the oscillating phenomenon may be attributed to a more complex coupling effects between the aerodynamic adjustments of gaseous jet and the movement of surrounding water, while the second one is not available from present high-speed photography. The detailed mechanics still needs further investigation.

The continuous oscillation finally results in the consequence of the jet Necking/Expansion-feedback process, as shown in Fig. 6. Again, the gas/water interfacial characteristics for present rectangular nozzle jets show highly similarity as the ones issuing from axisymmetric nozzles [3], [8], [23]-[25]. A typical characteristic in this process is the presence of a negative axial-velocity at the rear part of the nozzle. Meanwhile, the jet continually expands radially and its diameter has been larger than the external size of nozzle, as marked as the red arrow in Fig. 6(e). It was observed that this phenomenon induced tuyere refractory erosion [11]-[12].

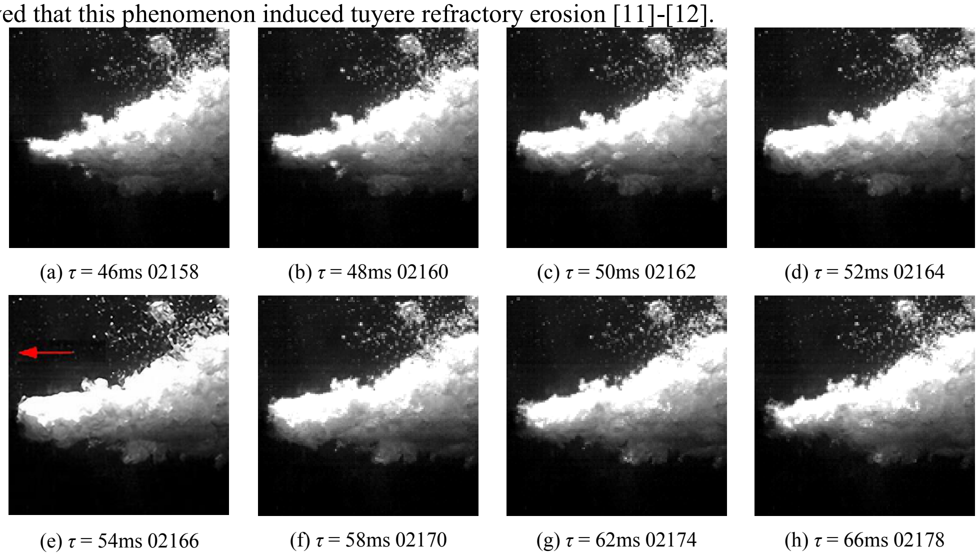
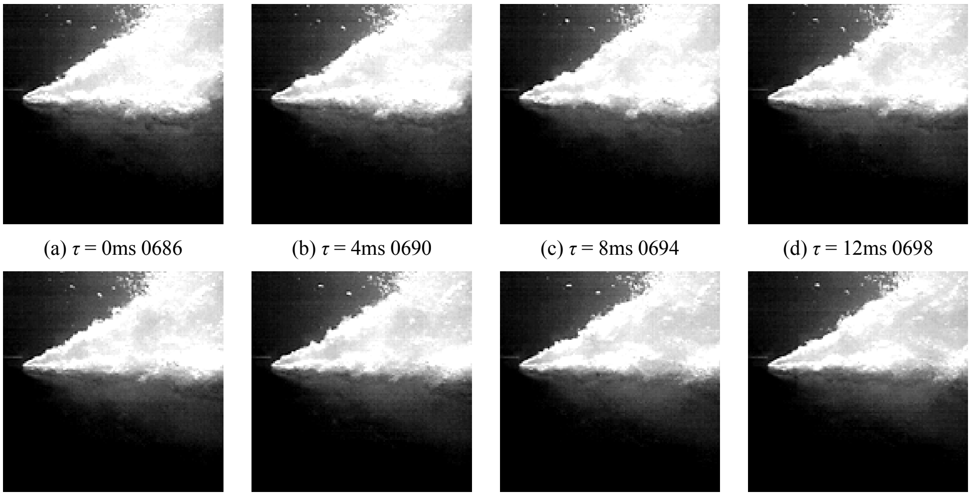


Fig. 6. High-speed photography of the jet Necking/Expansion-feedback process of a rectangular submerged under-expanded supersonic gaseous jet. Interframe time = 2ms~4ms. P_c = 1.1Mpa. The jet Mach number at the nozzle exit is Ma = 2.17.

As the nozzle pressure ratio further increased, the jet pattern started to deform. Fig. 7 are the sequences of under-expansion jets for 3.02Mpa case with a nozzle pressure ratio of 27.92, and a distinct 3D cross-like cross section jet gas/water boundary can be observed to form and grow from the nozzle exit. For this NPR condition, both the jet Necking/Bulging and Necking/Back-attack phenomena are not captured indicate a stable flow regime. A detailed analysis for the jet vibration frequency characteristic and gas/water interface deformation behavior can be found in the next sections.



(a) τ = 0ms 0686 (b) τ = 4ms 0690 (c) τ = 8ms 0694 (d) τ = 12ms 0698

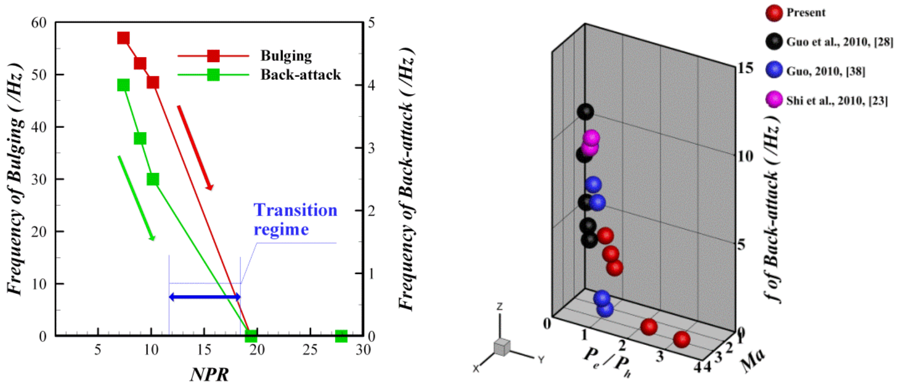
(e) τ = 16ms 0702 (f) τ = 20ms 0706 (g) τ = 24ms 0710 (h) τ = 28ms 0714

Fig. 7. High-speed photography of the jet structures of a rectangular submerged under-expanded supersonic gaseous jet. Interframe time = 4ms. P_c = 3.02Mpa. The jet Mach number of post-expansion-wave at the nozzle exit is Ma = 2.82.

3.2. Frequency analysis of the jet instability

From the high-speed photographs, the frequencies of the bulge and the back-attack are recorded and calculated, as seen in Fig. 8(a). For the full-expansion condition, the frequencies of the bulge and the back-attack events are 52.15Hz and 3.15Hz, respectively. As the nozzle pressure ratio increased, the frequencies of the two jet vibrations decrease and sharply down to zero during the transition regime. Previous study conducted by Guo [38] indicated a similar nonlinear attenuation curve for the two jet vibrations via nozzle pressure ratio based on an axisymmetric submerged nozzle tests. However, a deletion of experimental data during the transition regime makes difficulty to depict a complete attenuation curve in this paper.

Fig. 8(b) shows a comparison of frequencies for the jet back-attack phenomena between present rectangular nozzle tests with the ones from literatures based on the axisymmetric nozzles tests. Two parameters are chosen to evaluate the jet vibration instability, one is the Mach number, Ma, behind the incident inclined shock wave (due to over-expansion) or expansion wave (due to under-expansion), and the other is the exit pressure ratio, P_e/P_h, which represents the expansion condition of the gas jet at the nozzle exit. These two parameters are shown significant influence on the back-attack phenomenon according to previous experimental and numerical studies. From the figure, the present rectangular nozzle shows a slower attenuation characteristic. For similar value regime of the Mach number and exit pressure ratio, the present rectangular nozzle has higher frequency of the back-attack phenomenon. These results indicate that the submerged rectangular supersonic nozzle may produce more unsteady jet. However, the mechanics of the jet vibration is so complicated and is not sufficiently understood yet, the instability of the jet boundary is influenced by many factors such as turbulence, gas/water mixing, the Kelvin-Helmholz instability and the Richtmyer-Meshkov instability, et al. Additional experiments on axisymmetric nozzles and rectangular ones of the same geometric control parameters and operating parameters are needed to a direct comparison in future study.



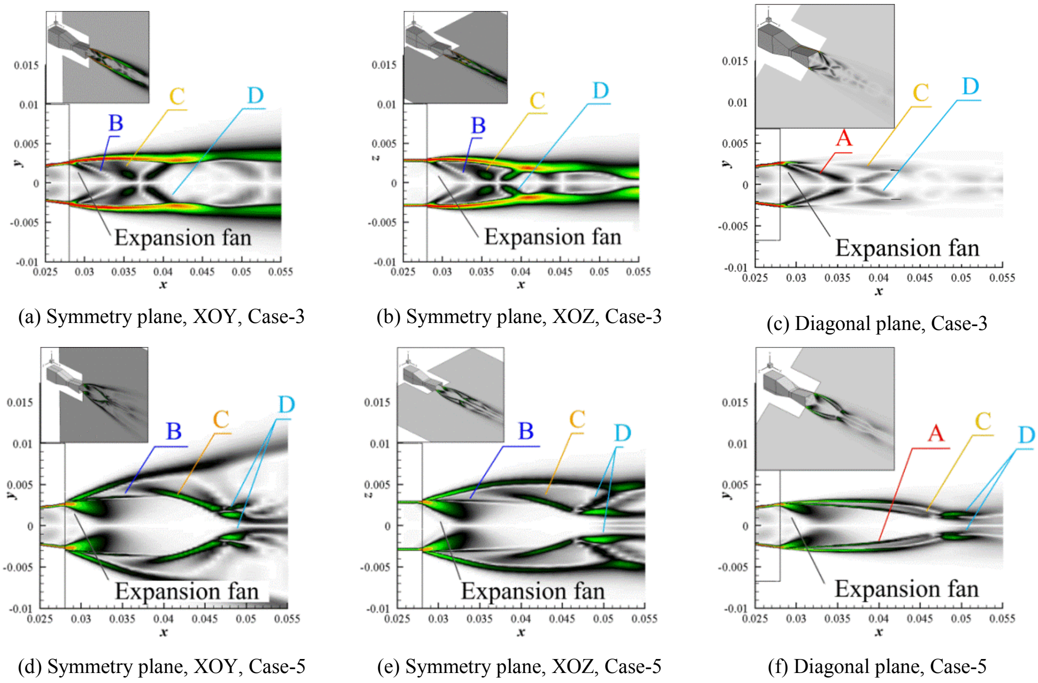
(a) Frequency of the two jet vibrations (b) Comparison to the axisymmetric nozzles

Fig. 8. Frequency characteristics of the jet instability: (a) Frequencies of the bulging and back-attack phenomena via the nozzle pressure ratio; (b) Comparison of frequencies for the jet back-attack phenomena between present tests with axisymmetric nozzles tests from literatures.

3.3. Correlations between the shock structures and jet gas/water interface

Fig. 9 shows the shock structures development on the two symmetry and diagonal planes via the nozzle total pressure. The shock wave structure is considered to be the key factor determining the expansion of the supersonic jet. Thus, visualization of the shock structure is very useful for understanding the flowfield. The two representative cases with nozzle total pressure P_{ON} = 1.1Mpa and 3.02Mpa are discussed here, respectively. Numerical schlieren pictures contoured by the plots of the absolute values of the first gradients at the grid nodes are used to help in identifying the shock waves in the flowfield downstreamed of the nozzle exit. It is shown that the shock structures differ considerably from the ones produced by axisymmetric nozzles, what's more, these shock patterns change distinctly as the nozzle total pressure increases from 1.1Mpa to 3.02Mpa. The shock waves captured in the numerical schlieren images can be classified into four categories, as marked by the letters A-D. These shock waves reproduce the key features of an under-expanded jet issuing from present rectangular or square-type nozzles, which correspond to recompression shock wave on the diagonal plane, recompression shock wave on the symmetry planes, intercepting shock wave both on the diagonal and symmetry planes, and recompression shock wave both on the symmetry and diagonal planes, respectively.

The shock waves A appear at the four corners of the nozzle exit and can only be captured on the diagonal plane. It is the key feature of under-expanded jet issuing from present rectangular or square-type nozzles that Prandtl-Meyer expansion fans are generated from the four edges of the nozzle exit, and the expansion fans from neighbouring edges interact in the corner regions, resulting in over-expanded flow. The lower static pressure than the ambient one in those over-expanded region resulting in the formation of recompression shock waves. The other three shock waves B-D are also similar to the ones produced by the jet issuing from a square nozzle [36] and the formation mechanics are not presented in this paper. The central angle of the expansion fan from the nozzle exit edge changes according to the total pressure P_{ON}. The larger central angle has two effects on the shock structure: larger over-expanded region is produced at the four corners which results in a wider recompression shock wave A shown in Fig. 9(f), and the fan spreads wider in the flowfield which results in an cross ring passage surrounded by the recompression shock wave D.



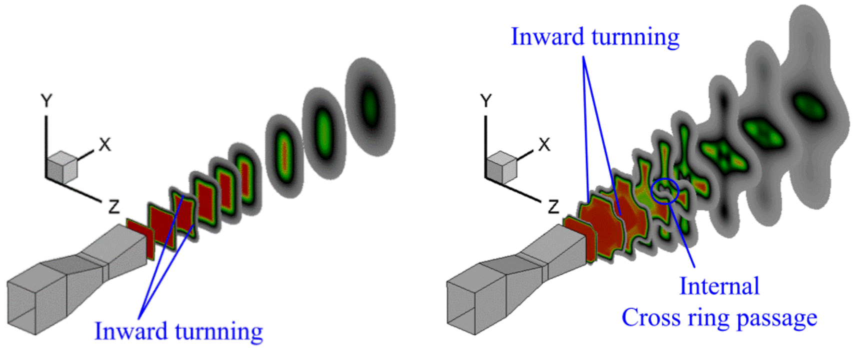
(a) Symmetry plane, XOY, Case-3 (b) Symmetry plane, XOZ, Case-3 (c) Diagonal plane, Case-3

(d) Symmetry plane, XOY, Case-5 (e) Symmetry plane, XOZ, Case-5 (f) Diagonal plane, Case-5

Fig. 9. Shock structures and jet boundary predicted by 3D numerical simulations, the numerical schlieren images in the upper and lower line obtained from P_{ON} = 1.1Mpa and 3.02Mpa, respectively.

Fig. 10 compares the representative total pressure cross sections of the jet from above two cases. It is clear that the nozzle total pressure affects the jet shape. As shown in Fig. 9 and Fig. 10, the cross shape of the jet cross section originates from the difference between jet expansion on the two symmetry and diagonal planes. When the nozzle total pressure is low, the jet boundary on the two symmetry planes, Fig. 9(a) and Fig. 9(b), expands nearly straight outward, and starts to slightly turn inward while encounter the recompression shock wave B, as also marked in Fig. 10(a). However, the jet boundary on the diagonal plane, Fig. 9(c), starts to turn inward immediately downstream of the nozzle exit because of the recompression shock wave A, and turns further inward as a result of the downstreamed intercepting shock wave C. As the nozzle total pressure increased, the difference in the expansion of the jet boundary between the symmetry and diagonal planes becomes substantial, that the limbs of the jet boundary on the symmetry planes extends outward two dimensionally while the jet boundaries at the four corners turn further inward, resulting in a remarkable cross-shaped jet cross section.

The preceding discussions focus mainly on the shock structures and jet boundary predicted by numerical simulations on the nozzle operating in air conditions. However, Loth et al. [8] and Qi et al. [27] have provided strong evidence that a shock wave cell structure for external expansion is present in the submerged jet, which is similar as the air conditions. For our present study, the submerged jet gas/water interface characteristics also show good agreement with the jet boundaries predicted by numerical simulations for the both two nozzle pressure ratios. These may indicate that a similar behavior of formation and development of shock structure and jet boundary via nozzle pressure ratio exist in a submerged jet issuing from a rectangular Laval nozzle. As indicated by Wang et al. [22] and Shi et al.[24], a shock-cell structure and a gas/water boundary co-exist in the flow field. Obviously, this kind of flow field usually cannot be stable. For the jets issuing from rectangular nozzles, more complex shock structure can form and develop than the axisymmetric nozzles, especially during over-expanded to slightly under-expanded conditions, when the over-expanded flow in the four corner regions as well as the recompression shock wave can produce a strong source of interface instability to result in necking/bulging and necking/back-attack phenomenon. Thus, the submerged supersonic jet from rectangular nozzle has higher instability than jet issuing from the axisymmetric nozzle under this expansion regime.



(a) P_{ON} = 1.1Mpa, NPR = 10.17 (b) P_{ON} = 3.02Mpa, NPR = 27.92

Fig. 10. Frequency characteristics of the jet instability: (a) Frequencies of the bulging and back-attack phenomena via the nozzle pressure ratio;(b) Comparison of frequencies for the jet back-attack phenomena between present tests with axisymmetric nozzles tests from literatures.

4. Conclusions

(i) As the nozzle pressure ratio increased, two distinct flow regimes can be observed: One that showed unstable gas/water interfacial characteristics for nozzle pressure ratio, NPR or Po/Pa $\leqslant$ 10.17 when the jet pattern showed similar shape as the one issuing from axisymmetric nozzles, and the other with stable jet pattern for NPR > 18.48 when a 3D cross-like cross section jet gas/water boundary started to form and grow from the nozzle exit.

(ii) The jet Necking/Bulging and Necking/Back-attack phenomena are observed for nozzle jets operate in over-expanded conditions to moderate under-expanded conditions. For the full-expansion condition, the frequencies of the bulge and the back-attack events are 52.15Hz and 3.15Hz, respectively. As the nozzle pressure ratio increased, the frequencies of the two jet vibrations decrease and sharply down to zero during the transition regime.

(iii) The present submerged rectangular nozzle jet has higher frequency of the back-attack oscillation phenomenon comparison to the axisymmetric ones; indicate that the submerged rectangular supersonic nozzle may produce more unsteady submerged jet.

(iv) The submerged jet gas/water interface characteristics show good agreement with the jet boundaries predicted by numerical simulations. The over-expanded flow in the four corner regions as well as the recompression shock wave can produce a strong source of interface instability to result in necking/bulging and necking/back-attack phenomenon during over-expanded to slightly under-expanded conditions. Thus, the submerged supersonic jet from rectangular nozzle has higher instability than jet issuing from the axisymmetric nozzle under this expansion regime. However, additional experiments with more operating conditions as well as refined measurements are needed to understand the detailed mechanics behind.

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